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THE EFFECT OF PRESTRAIN AND WATER SOAK ON THE MECHANICAL PERFORMANCE OF CROSS-PLIED COMPOSITES

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THE EFFECT OF PRESTRAIN AND WATER SOAK ON THE MECHANICAL PERFORMANCE OF CROSSPLIED COMPOSITES

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FOREWARD

The research reported herein was conducted by the staff of Monsanto/Washington University Association under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 87, ONR contract authority NR 356-484/4-13-66, entitled "Development of High Performance Composites".

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The Effect of Prestrain and Water Soak on the Mechanical Performance of Crossplied Composites

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ABSTRACT

The mechanical performance of 0°-90° crossplied glass-epoxy laminates was evaluated under static tensile loading along the longitudinal direction. The effects of both prestraining and water soaking were considered. Generally, the stress and strain associated with initial cracking increased with prestrain even in the presence of water. The ultimate stress and strain continuously decreased. However, under the most adverse conditions considered (greatest prestrain and water soak) this decrease was less than 20 percent. It is concluded that a reasonable static design limit stress would be 2/3 the ultimate tensile stress.

Introduction

Orthotropic crossply laminates are attractive for engineering applications because they offer a reasonable compromise between the extreme anisotropy of unidirectional systems and the quasi-isotropy of random composites. Designing with such materials, however, is frequently complicated by the ambiguity of the term "failure stress." Waddoups (1) has discussed this problem and pointed out that for design purposes the limiting stress of crossplies may be based on either initial cracking of the transverse plies or the catastrophic failure of the composite.

For typical glass-epoxy unidirectional laminates there is a factor of 5 difference between the longitudinal and transverse ultimate strains. This behavior is retained in crossply laminates. Thus, if failure of the crossply is based on initial cracking, the load carrying capacity of the system will be less than 20 percent of the load carrying capacity based upon catastrophic failure of the longitudinal plies.

Several investigators have studied the problem of determining the appropriate design stress for crossplied composites under both static and dynamic conditions. Broutman (2) concluded that in glass-epoxy systems, initial transverse cracking causes subsequent deterioration if the system is subjected to cyclic loading. In contrast, Doner (3)

concluded from similar studies of graphite-epoxy systems that there is no deterioration in stiffness or strength due to cyclic loading even after pronounced transverse cracking. It should be noted that in the graphite-epoxy composites the longitudinal ultimate strain is relatively low and is nearly equal to the transverse ultimate strain. There is, therefore, very little mismatch in the strain capacities of the various layers. From the above investigations, Lavengood (4) reasoned that the mechanical performance of the glass-epoxy crossplied system might be improved by increasing the deformability of the transverse laminae, thereby reducing the strain mismatch. This was accomplished by using a lower modulus epoxy which is more ductile than the usual matrix materials. This led to a significant increase in the strength of the crossplies with a negligible decrease in stiffness. Specifically, the ultimate strength of the composite was increased by 10 percent while the initial cracking stress was doubled. One disadvantage of this approach is that the lower thermal resistance of these matrices reduces the maximum service temperature of the composites.

Whitney (5) recently reported studies which included both glass-epoxy and graphite-epoxy crossplied laminates. His results show that when a specimen is subjected to repeated tensile loadings, transverse ply failure causes hysteresis effects on the first cycle which are subsequently dissipated.

No significant loss in strength was noted after five cycles. A loss in modulus occurs in the first cycle, of course, but no further change in stiffness was found on subsequent loadings. Additional hysteresis effects were noted for each cycle if the cyclic loadings were imposed at progressively higher strain levels. Whitney therefore concluded that for crossplied laminates with fibers in the principal load direction, 2/3 of the ultimate tensile stress would be a reasonable limit for static design but that ultimate strength for fatigue applications should be based on first ply failure, i.e., initial cracking. The above studies did not consider environmental effects.

The objective of this study is to determine the effect of static prestrain and water soaking upon the strength of crossplied glass-epoxy laminates. The specific characteristics to be studied are 1) the composite stress and strain at initial cracking, 2) the primary, secondary, and unloading Young's moduli, and 3) the ultimate composite stress and strain. The role of transverse cracking in accelerating environmental attack will be considered.

Materials

All composites were made with Shell Epon 828 plus 20 phr Shell Curing Agent Z. The reinforcement is 1062-T-6 E glass roving supplied by Pittsburgh Plate Glass Company with a proprietary, epoxy compatible, coupling agent.

Experimental Details

Crossply laminates were prepared by filament winding on rectangular mandrels, 8 inches square and 1/2-inch thick. The procedure was identical to that reported in (4).

Tensile tests were run in an Instron tester at a cross-head speed of 0.05 in/min (0.013 min^{-1} strain rate in the 3-inch gauge length of the specimens). A 2-inch extensometer was used to continuously monitor strains. All tests were conducted at room temperature (75 F).

Test Results and Discussion

Typical stress-strain curves for the virgin crossplies and the constituent longitudinal and transverse layers are shown in Figure 1. As expected, both the strength and stiffness of the laminate are intermediate to those of the unidirectional constituents. In contrast with the other two, however, there is a pronounced discontinuity in the slope of the crossply stress-strain curve. This knee, at about 0.7 percent strain, is a result of extensive cracking of the transverse layers. The resulting stress-strain curve has two linear portions. A primary modulus may be calculated from the curve between the stress-free state and the knee, while a secondary modulus is related to the curve between the knee and ultimate failure. Average properties of these control specimens, and all subsequent tests, are tabulated in Table I.

Figure 2 shows stress-strain curves for specimens strained to 0.5 percent and then unloaded. The 0.5 percent prestrain level is approximately 2/3 of the strain associated with initial cracking (IC) in the control tests. Both the loading and unloading paths are linear and there is no residual strain. The mechanical properties upon reloading to fracture are essentially the same as those for specimens with no prestrain history (see Table I).

The stress-strain curves resulting from prestraining to 1.0 percent (4/3 IC) and 1.5 percent (2 IC) are shown in Figure 3 and Figure 4 respectively. In both cases unloading from the prestrained state was linear and resulted in small residual strains (0.06 percent). The unloading modulus decreased as the level of prestrain increased. In both cases, no recovery of the residual strain was noted in a two-hour period in the stress-free state. Hence, it was concluded that the residual strain is permanent plastic deformation and behavior is somewhat analogous to that of metal unloaded from a stress-state exceeding the yield stress. Deformational response during prestraining is summarized in Table II.

Tensile stress-strain curves for 3/4 IC and 2 IC specimens are shown in Figure 5 and Figure 6 respectively. On reloading, the primary Young's modulus is nearly equal to the unloading modulus, for all prestrain levels. The transverse cracking resumes at a level greater than or equal to the original prestrain. The transverse cracking stress therefore increases in a similar manner.

The first series of water soak tests was with unidirectional specimens and included tests after 1,2,4,7,10,21 and 42 days in water at 25,50,75 and 100 degrees Centigrade. The purpose of these tests was to provide a rational basis for the selection of a standard immersion time and temperature for the crossply samples. Specimens were 1/8-inch square and 3 inches long with fibers aligned in the axial direction. All specimens were tested in three-point flexure on a 2-inch span. The results are shown in Figure 7. Each data point represents the average of four tests. From these curves a standard cycle time of 18 days at 75 C was chosen as one which produces significant degradation in a reasonable time period.

Typical stress-strain curves for crossply specimens with no prestrain, before and after water soaking, may be compared in Figure 8. Pertinent stresses, strains and moduli are tabulated in Table I. Both curves exhibit the characteristic knee associated with initial cracking, i.e., an abrupt decrease in stiffness following the first cracks in transverse layers. The most pronounced effect of the water soaking is to reduce both the stress and strain at the knee by almost 25 percent. The corresponding ultimate stress and strain values differ less than 5 percent.

There are two important observations to be made. First, for designs based on the initial cracking stress of a new material, a design allowable stress of 2/3 IC may produce stress levels dangerously close to failure in a material

which is subsequently exposed to water. The second point is that the ultimate tensile strength degradation of the crossply is much less than that of the unidirection flexural specimens. Although it is frequently not wise to compare tensile and flexural results, the differences here are so marked that it must reflect more than just a change in loading mode. The other significant difference in these specimens is that the fibers in the 0 degree layers of the crossplies were not exposed directly to the water. The process of gluing on tabs effectively encapsulates the ends of these specimens. Therefore, water cannot wick along the innerface until it passes through the layer of epoxy glue. The great difference in water resistance suggests that wicking is an important factor in the degradation of fiberglass reinforced epoxy.

The stress-strain curve for water-soaked specimens with 0.5 percent prestrain is shown in Figure 9. This level of prestrain had no effect on either strength or moduli. The decrease in properties compared with virgin specimens may be attributed solely to the water soak.

Figures 10 and 11 show the stress-strain curves for water-soaked composites which had previously been strained to 1.0 and 1.5 percent respectively. The 1.0 specimens have a knee at 0.7 percent and 20 ksi. This is higher than the comparable nonprestrained sample, but, of course, here the knee reflects the continuation of transverse cracking rather than the onset. In contrast, the 1.5 percent material has no

knee and is linear to failure. The ultimate strain is 1.5 percent which coincides with the prestrain level. In both cases, the ultimate properties are significantly lower than either the nonimmersed samples or the nonprestrained samples. There is clearly a synergistic effect. After immersion the ultimate strength retention is 89 percent for the 4/3 IC samples and 80 percent for the 2 IC material. It can therefore be concluded that prestrains above the initial cracking level greatly accelerate the attack of the water.

Summary and Conclusions

The effects of prestrain are summarized in Figures 12a and 12b. For static applications not involving hostile environments, Figure 12a shows that prestraining does not cause any degradation of properties. Therefore, designing on the basis of 2/3 of ultimate stress would be acceptable. In the more normal situation, however, some deleterious environmental effects must be expected. In this case, Figure 12b shows that the degradation of ultimate properties is greatly accelerated by prestrains above the initial cracking level. The highest prestrain of 1.5 percent corresponds to approximately 2/3 of the ultimate stress of virgin material. The 19 percent loss in strength of these water-soaked samples shows that large safety factors must be used when design is based on ultimate stress of virgin material. The more conservative approach would be to design on the basis of the onset of transverse cracking.

Table I

	Control	Fracture After Prestrain to 0.5%	Fracture After Prestrain to 1.0%	Fracture After Prestrain to 1.5%	Fracture After H_2O Soak	Fracture After Prestrain and H_2O Soak 0.5%	Fracture After Prestrain and H_2O Soak 1.0%	Fracture After Prestrain and H_2O Soak 1.5%
Primary Young's Modulus x 10^6 psi	3.13	3.20	2.70	2.59	2.99	3.03	2.85	2.86
Composite stress at initial cracking (IC) x 10^3 psi	21.8	23.7	28.45	44.32	16.6	15.8	19.96	LINEAR TO FAILURE
Percent tensile strain at initial cracking	0.70	0.74	1.0	1.71	0.55	0.53	0.70	
Secondary Young's Modulus x 10^6 psi	2.23	2.15	2.28	1.98	2.25	2.31	2.39	
Composite stress at ultimate failure x 10^3 psi	53.5	53.3	55.7	54.5	50.5	51.6	47.0	43.0
Percent ultimate tensile strain	2.20	2.10	2.30	2.23	2.07	2.10	1.80	1.50

Table II

Deformational Behavior During Prestrain Cycle

	Prestrain Level		
	0.5%	1.0%	1.5%
Primary Modulus	3.00	2.98	2.84
Secondary Modulus	——	2.08	2.15
Unloading Modulus	3.00	2.75	2.55
Permanent Strain (%)	0.000	0.060	0.055

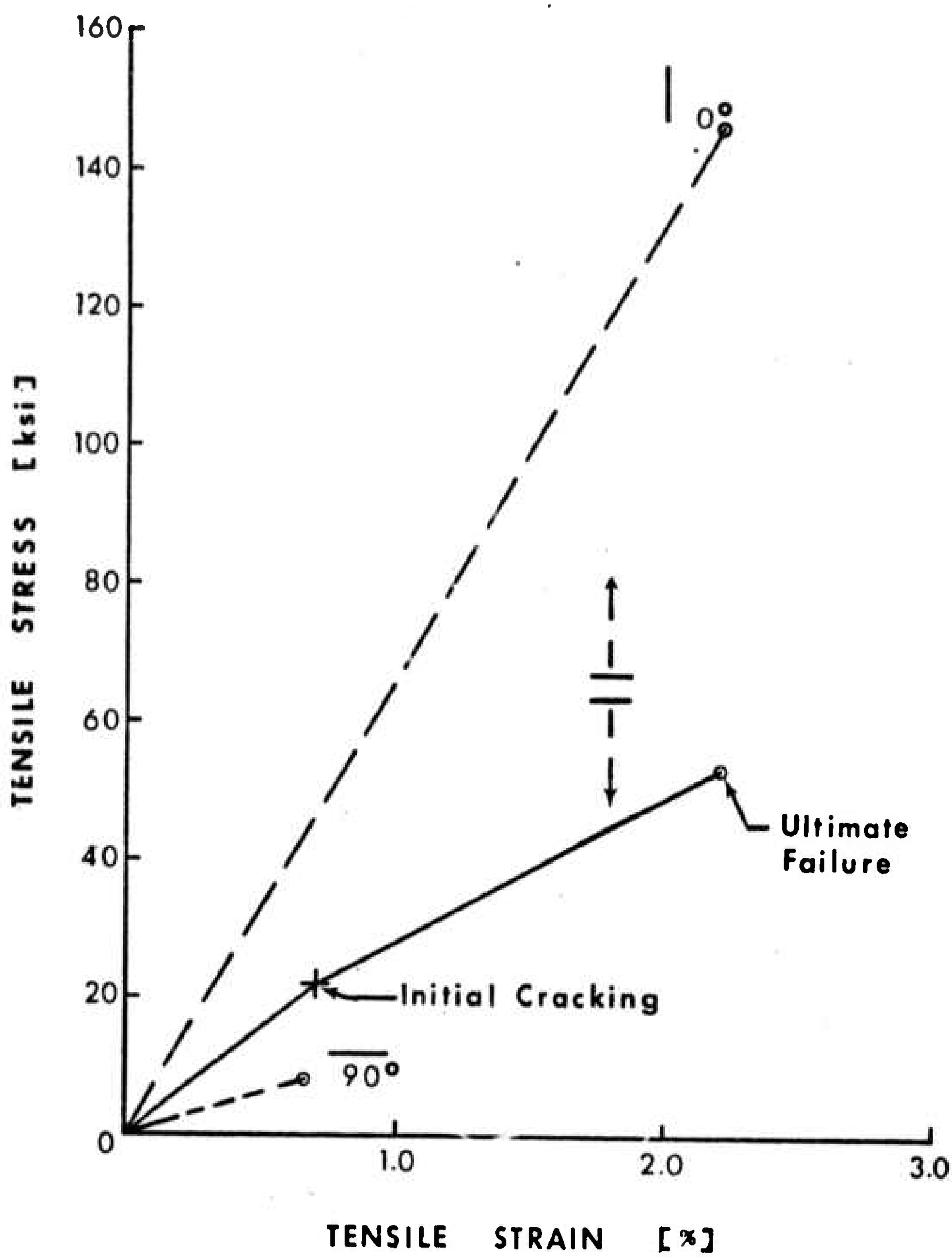

Figure 1 - Typical stress-strain curves for the virgin crossplies and the constituent longitudinal and transverse layers.

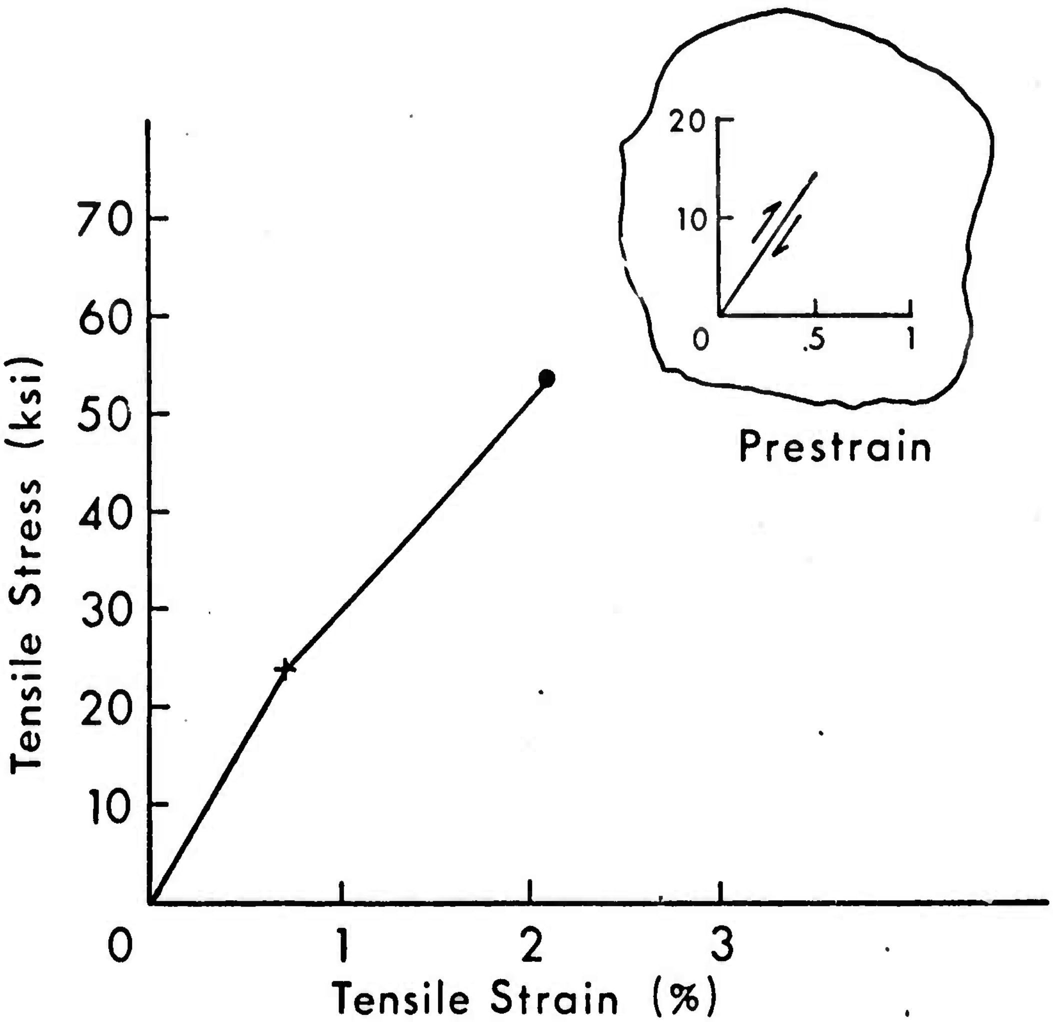

Figure 2 - Stress-strain curves for specimens prestrained to 0.5%.

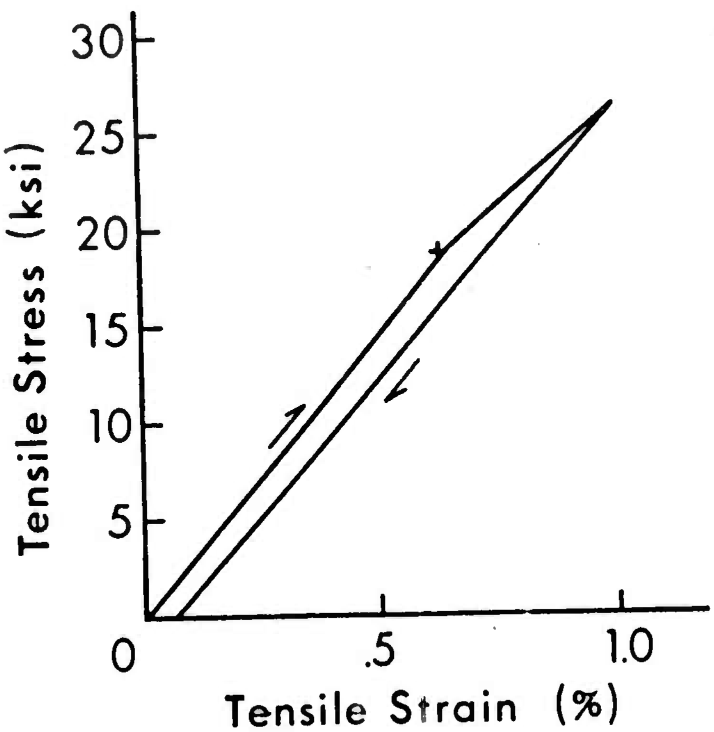

Figure 3 - Stress-strain curve for specimens prestrain to 1.0%.

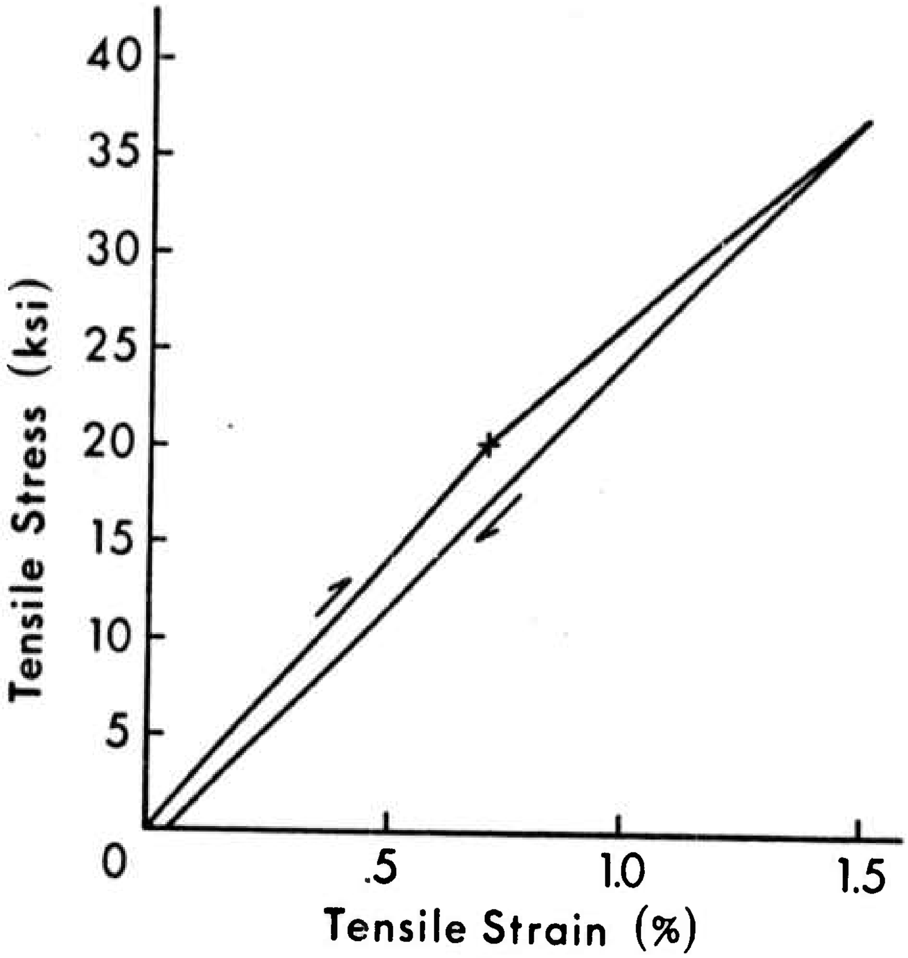

Figure 4 - Stress-strain curve for specimens prestrain to 1.5%.

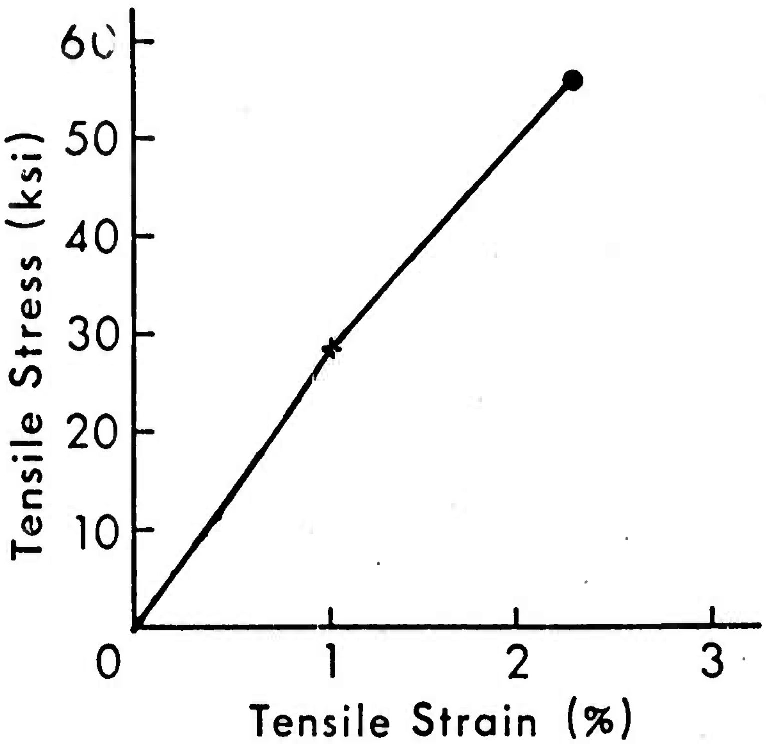

Figure 5 - Stress-strain curve subsequent to 1.0% prestrain.

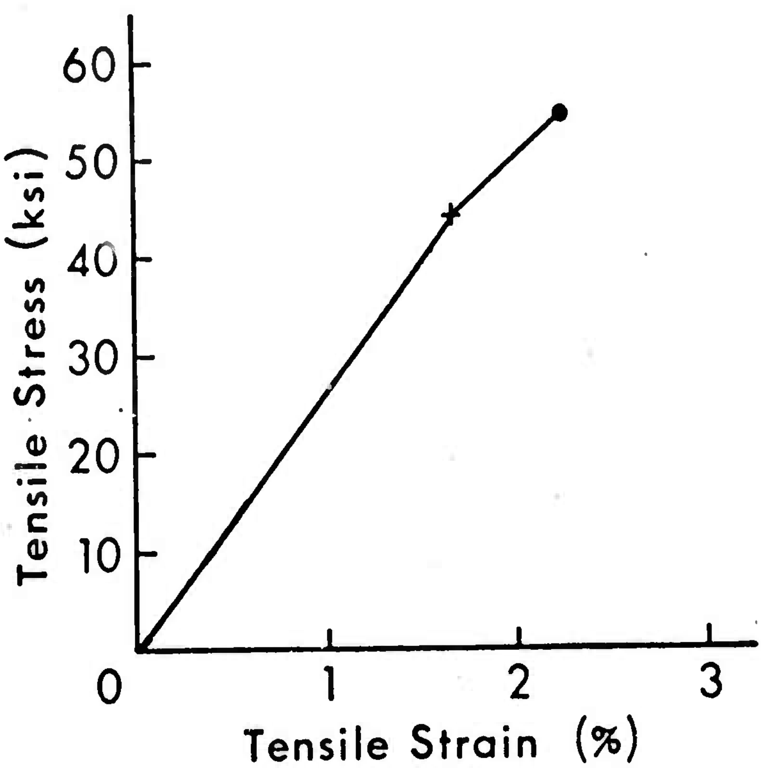

Figure 6 - Stress-strain curve subsequent to 1.5% prestrain.

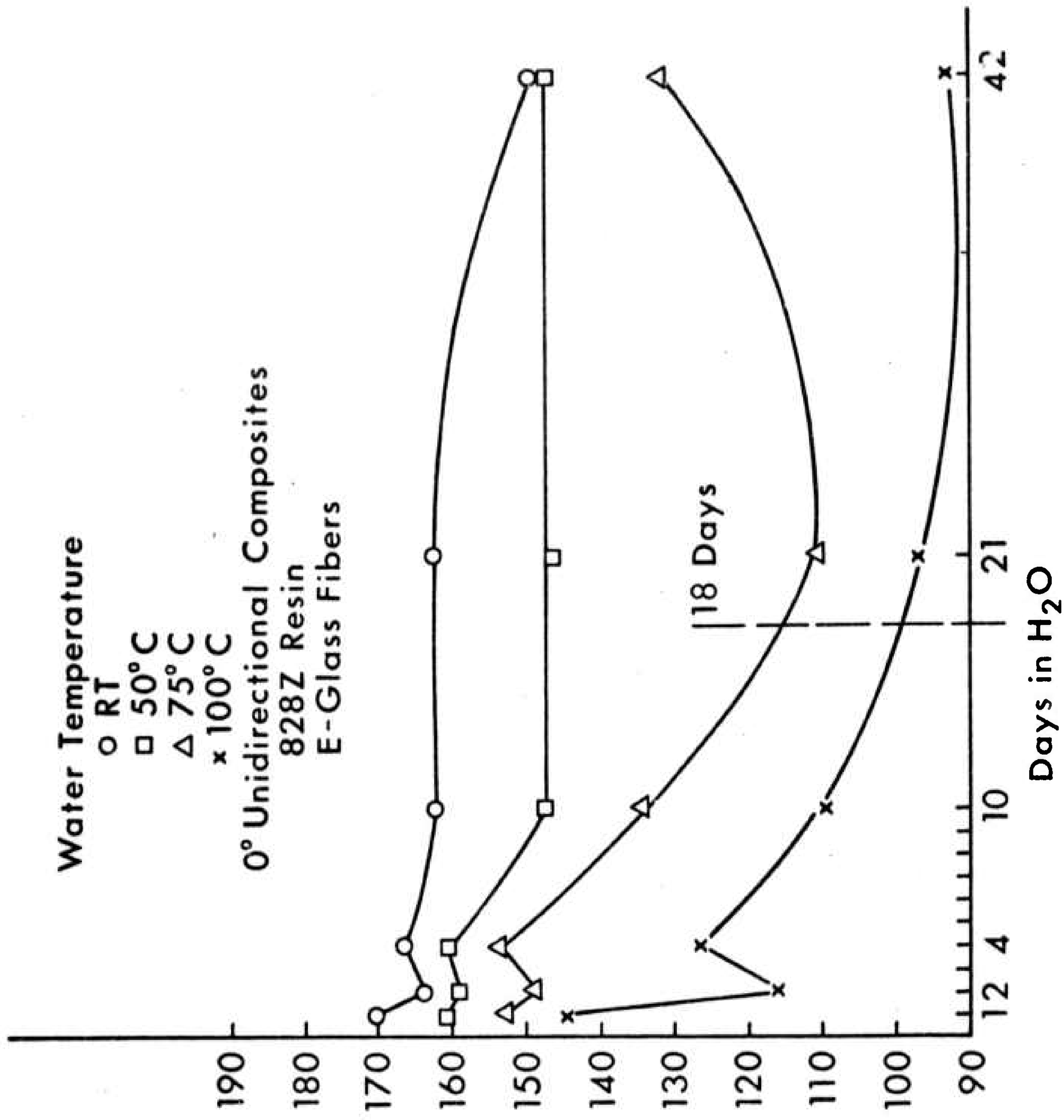

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Figure 7 - Effect of water soaking on flexure strength.

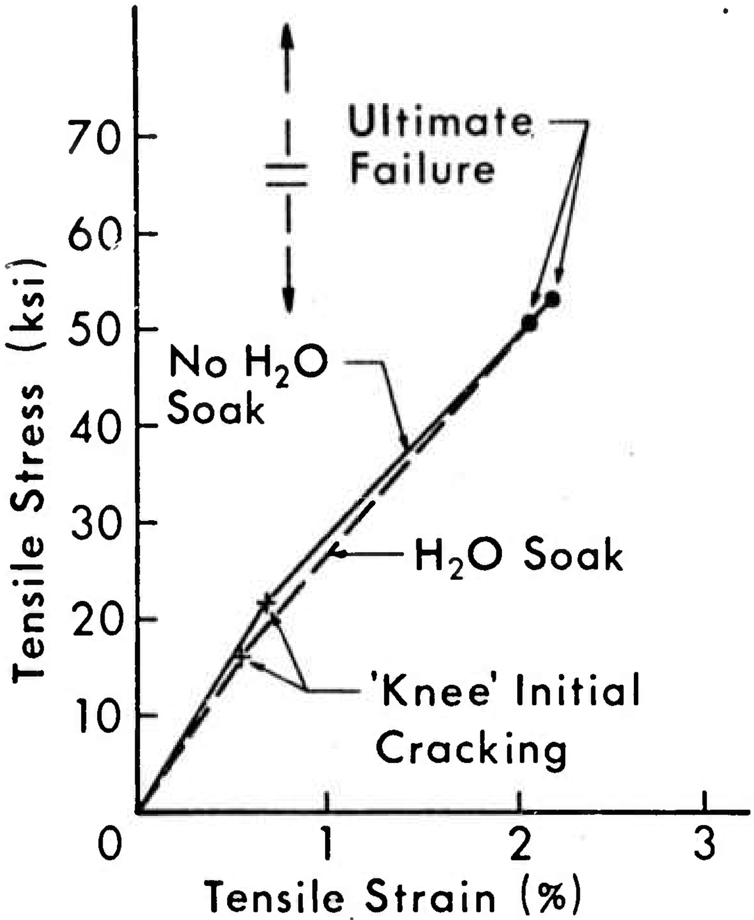

Figure 8 - Stress-strain curve for crossply with no prestrain before and after water soaking.

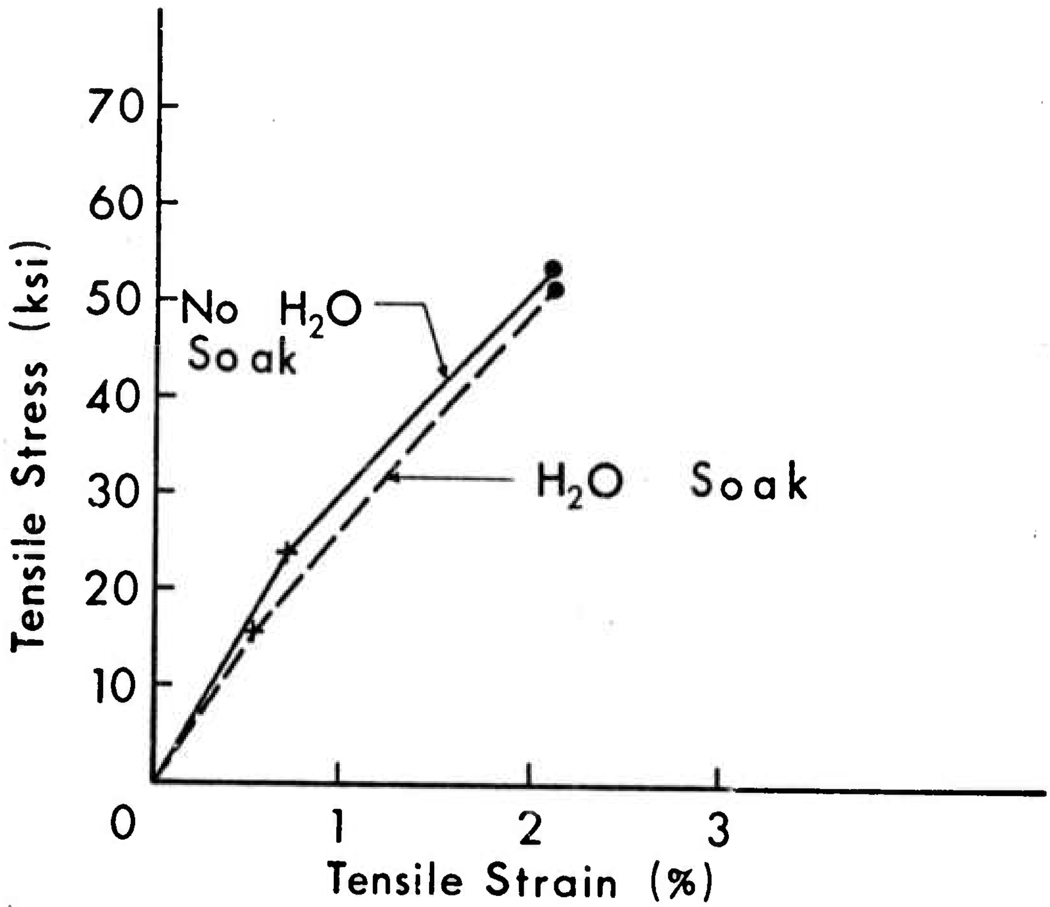

Figure 9 - Stress-strain curve for crossply with 0.5% prestrain and water soaking.

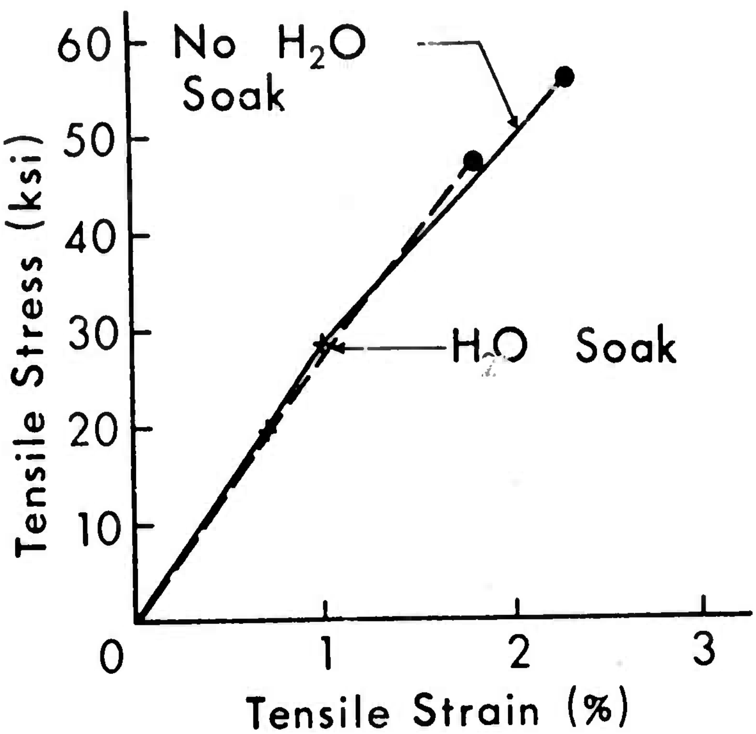

Figure 10 - Stress-strain curve for crossply with 1.0% prestrain and water soaking.

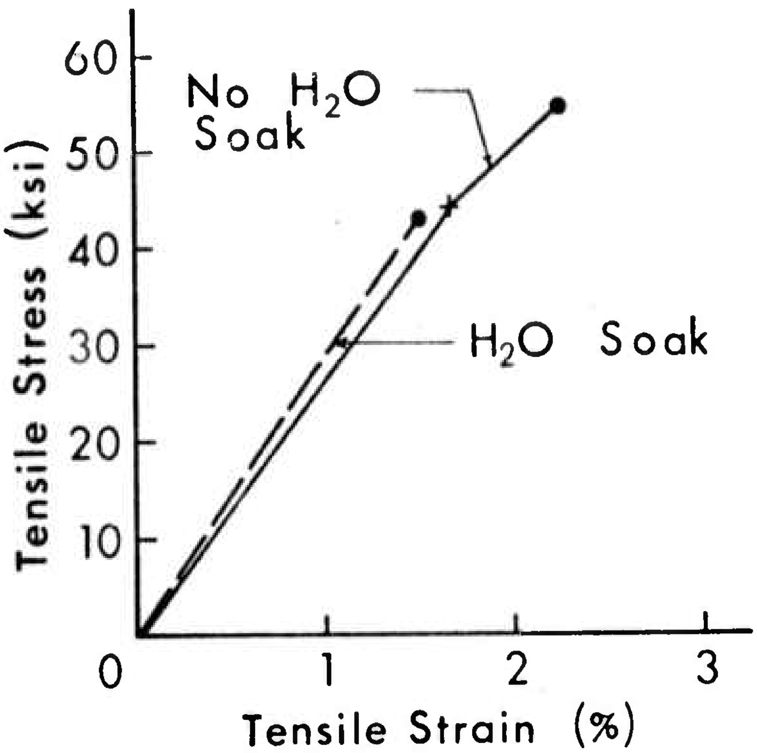

Figure 11 - Stress-strain curve for crossply with 1.5% prestrain and water soaking.

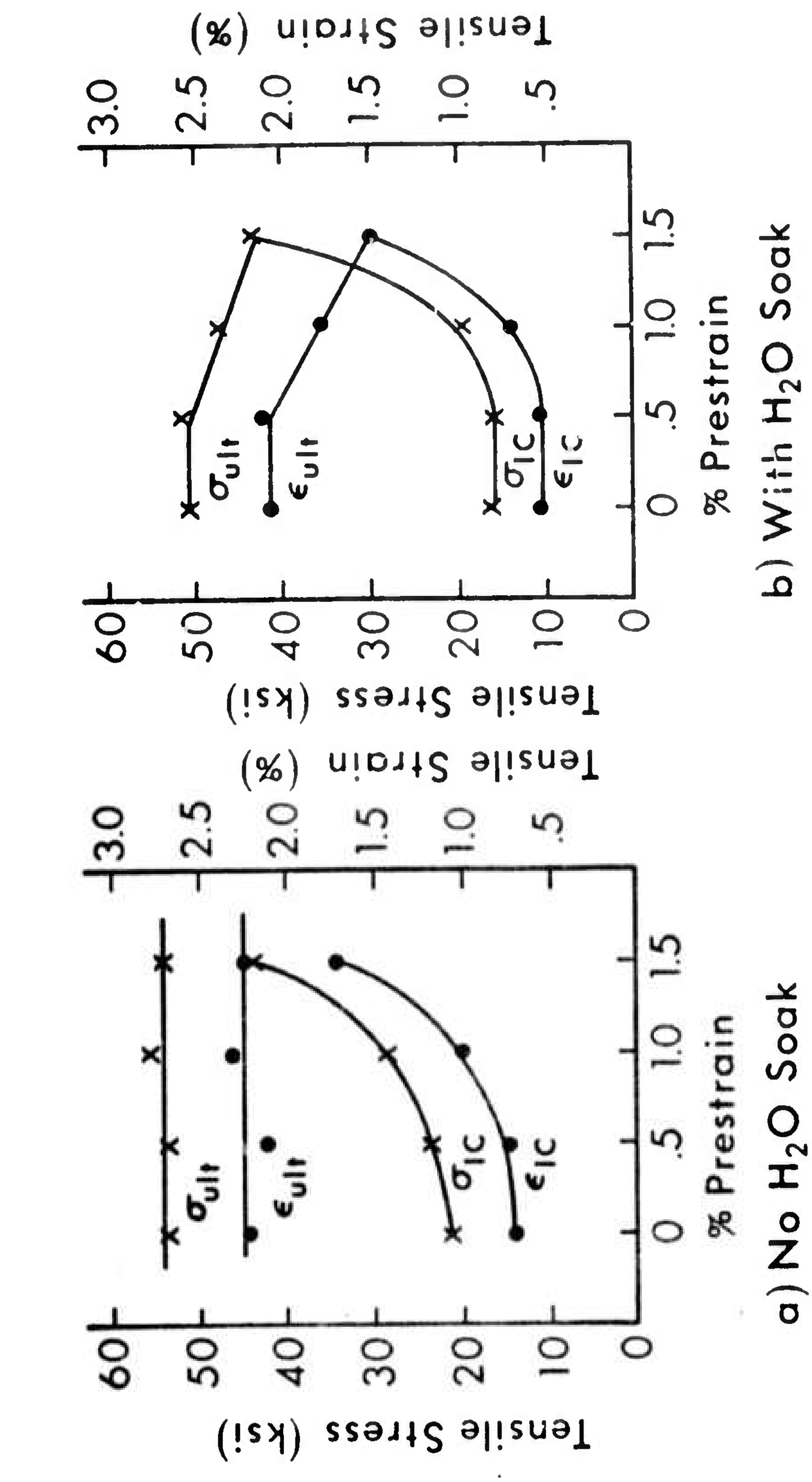

Figure 12 - Summary of effects of prestrain.

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